

EPR Experiment and Two-Photon Interferometry  
— Report of A Two-Photon Interference Experiment —

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ABSTRACT

After a very brief review of the historical EPR experiments, this paper reports a new two-photon interference type EPR experiment. A two-photon state was generated by optical parametric down conversion. Pairs of light quanta with degenerate frequency but divergent directions of propagation were sent to two independent Michelson interferometers. First and second order interference effects were studied. Different than other reports, we observed that the second order interference visibility vanished when the optical path difference of the interferometers were much less than the coherence length of the pumping laser beam. However, we also observed that the second order interference behaved differently depending on whether the interferometers were set at equal or different optical path differences.

1. Historical EPR Experiments

In May 1935, Einstein, Podolsky and Rosen published a paper in the form of a paradox to show quantum mechanics fails to provide a complete description of physical reality. They put a question as the title of the paper: "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"<sup>(1)</sup>

It seemed to EPR that a necessary requirement for a complete physical theory was the following:

(1) Every element of physical reality must have a counterpart in a complete physical theory.

EPR also suggested the following criterion for recognizing an element of reality, which seemed to them a sufficient criterion:

(2) If, without in any way disturbing the system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity.

What EPR wished to do with their criteria for reality was to show that the quantum mechanics wavefunction cannot provide a complete description of all physically significant factors (or "elements of reality") existing within a system.

A clear example of such system was proposed by David Bohm in 1951.<sup>(2)</sup> Bohm's *gedankenexperiment* concerned a pair of spatially separated spin-1/2 particles produced somehow in a singlet state, for example, by disassociation of the spin-0 system. The spin part of the state may be written as:

$$|\Psi\rangle = \frac{1}{\sqrt{2}} [ |\hat{n}_1^+\rangle \otimes |\hat{n}_2^-\rangle - |\hat{n}_1^-\rangle \otimes |\hat{n}_2^+\rangle ] \quad (1)$$

where  $|\hat{n}_1^\pm\rangle$  quantum mechanically describes a state in which particle 1 or 2 has spin "up" or "down" respectively along the direction  $\hat{n}$ . Since the singlet state  $|\Psi\rangle$  is spherically symmetric,  $\hat{n}$  can be specified to be any direction. Suppose one can set up his

experiment to measure the spin of the particles in any direction and he wants to measure the spin of particle 1 along the  $\hat{x}$  axis. What he can measure is not predetermined by the quantum state  $|\Psi\rangle$ . However from  $|\Psi\rangle$  one can predict with certainty that if particle 1 is found to have its spin parallel to the  $\hat{x}$  axis, then particle 2 will immediately be found to have its spin antiparallel to the  $\hat{x}$  axis if the  $\hat{x}$  component of its spin is also measured. Thus one can arrange his experimental apparatus in such a way that he can predict the value of the  $\hat{x}$  component of spin of particle 2 presumably without any way disturbing it. According to the criterion, the  $\hat{x}$  component of spin of particle 2 is an element of reality. Likewise, one can also arrange his apparatus so that he can predict any other component of the spin of particle 2 without interacting with it. The conclusion would be all the  $\hat{x}$ ,  $\hat{y}$ ,  $\hat{z}$  components of the spin of each particle are the elements of physical reality, and of course all the  $\sigma_x$ ,  $\sigma_y$ ,  $\sigma_z$ , must exist without considering which component is being measured. But this is not true in quantum mechanics, the wavefunction can specify, at most, only one of the components at a time with complete precision. The conclusion is that the wavefunction does not provide a complete description of all elements of physical reality.

The existence of an entangled quantum state is the heart of the E.P.R. argument. It must be a entangled pure state. There must be a definite phase relation among the amplitudes of the state. Does any such quantum state exist? Yes, experiments have demonstrated the existence of such quantum states.

### (1). Positronium Annihilation

The existence of the pure two photon singlet state of the positronium annihilation was predicted by J. A. Wheeler in late 40's and experimentally proved by C. S. Wu and I. Shaknov in 1950.<sup>(3)</sup>

### (2). Atomic Cascade Decay

Atomic cascade decay were introduced to EPR experiments in 1970's. Several groups of researchers have demonstrated the existence of the pure two photon EPR state from the atomic cascade decay. Since 1965, when J. Bell provided a theory to show that the local deterministic hidden variable theory has different predictions from those of quantum mechanics in some special experimental situations, experiments have been performed to test his inequalities using the light quanta pair prepared from the atomic cascade decay.<sup>(4)</sup> Even though it is hard to believe that the photon pair emitted from the atomic cascade decay are phase correlated when considering the rather long life time intermediate state of the atom, the experimental results seemed to show that the phase correlation is really there. Bell's inequalities are violated in most of the experiments.

However, none of the above experiments has completely satisfied the serious physics community. One of the problems is the efficiency "loophole". The emission of the photon pairs do not have a defined K vector direction in both the positronium annihilation and atomic cascade decay experiments. The emission is symmetric in  $4\pi$  solid angle and the collection angle can not be very large. The low collection efficiency in these experiments has been criticized by dozens of physicists and philosophers. It was concluded that none of these experiments was a compelling test of Bell's inequality, or in other words that none of these experiments has really demonstrated the phase correlation of the EPR state.

### (3). Parametric Down Conversion

The first EPR experiment using light quanta pair generated by optical parametric down conversion<sup>(5)</sup> is illustrated in figure 1. The two quanta polarization pure quantum state is prepared with the help of beam splitter.

Parametric down conversion generates photon pairs with definite  $\mathbf{K}$  vectors. The collection efficiency could be 100%. It is also different than all the other EPR experiments in that the entangled pure quantum state is "made" by people instead of God. The down conversion state starts from a circular or linear polarized eigenstate depending on whether quarter wave plate or half wave plate are used. It seems like "nothing hidden" in this experiment. With the help of a 50-50 beam splitter, the following quantum states can be "made",

$$|\Psi\rangle = \frac{1}{2} e^{i(\alpha+\beta)} [ |R_1\rangle \otimes |R_2\rangle - |L_1\rangle \otimes |L_2\rangle ] \\ + \frac{1}{2} e^{i(\alpha_1+\beta_1)} |R_1\rangle \otimes |L_1\rangle - \frac{1}{2} e^{i(\alpha_2+\beta_2)} |R_2\rangle \otimes |L_2\rangle$$

or,

$$|\Psi\rangle = \frac{1}{2} e^{i(\alpha+\beta)} [ |X_1\rangle \otimes |Y_2\rangle + |Y_1\rangle \otimes |X_2\rangle ] \\ + \frac{1}{2} e^{i(\alpha_1+\beta_1)} |X_1\rangle \otimes |Y_1\rangle + \frac{1}{2} e^{i(\alpha_2+\beta_2)} |Y_2\rangle \otimes |X_2\rangle$$

respectively. For the coincidence measurement, only the first two terms contribute. They are the singlet states needed for the EPR experiments. For the coincidence measurements, one would have:

$$|\langle X_1 Y_2 | \Psi \rangle|^2 = |\langle Y_1 X_2 | \Psi \rangle|^2 = 50\% \\ |\langle X_1 X_2 | \Psi \rangle|^2 = |\langle Y_1 Y_2 | \Psi \rangle|^2 = 0.$$

and

$$|\langle X_1(\theta_1) X_2(\theta_2) | \Psi \rangle|^2 \\ = \frac{1}{2} \sin^2(\theta_1 + \theta_2) = \frac{1}{2} \sin^2 \varphi$$

The experimental results agreed with the quantum mechanics prediction very well. <sup>(5),(6)</sup>

## 2. Two Photon Interference Experiment

All the above historical EPR experiments are concerned polarization correlation measurements. J. D. Franson <sup>(7)</sup> proposed a new type EPR experiment for measurement of position and time correlation in contrast to the historical measurement of polarization correlation. This proposed experiment is also concerned to be a two-photon interference experiment. This experiment may be simply illustrated in Fig. 2: a pair of time and frequency correlated photons is generated. One travels to the left, another travels to the right and both goes through a independent interferometer. The optical path difference  $\Delta L_1 = L_1 - S_1$  and  $\Delta L_2 = L_2 - S_2$  can be arranged to be shorter or longer than the coherence length of the down converted field.

Case 1.  $\Delta L_1 < \text{coherence length}$

Both interferometer I and II (or one of them, if only one interferometer satisfy the condition) will have independent first order interference,

$$R_i = R_{oi} \cos^2(\delta_i/2), \quad (2)$$

where  $R_i$  is the counting rate of the  $i$ th detector,  $\delta_i$  is the phase difference between the  $L_i$  and  $S_i$  optical paths of the independent interferometer. The classical coincidence rate is expected to be,

$$R_c = R_{oc} \cos^2(\delta_1/2) \cos^2(\delta_2/2). \quad (3)$$

The same result comes from quantum calculation.

Case 2.  $\Delta L_1 >$  coherence length

The first order interference disappears from both interferometers. It was suggested by Franson that the following coincidence detection probability amplitudes can be treated coherently,

(photon #1 travel from path  $S_1$ )

⊗ (photon #2 travel from path  $S_2$ )

and

(photon #1 travel from path  $L_1$ )

⊗ (photon #2 travel from path  $L_2$ ),

if the travel time difference between the long and short paths of the two interferometers are equal.

The amplitudes:

(photon #1 travel from path  $S_1$ )

⊗ (photon #2 travel from path  $L_2$ )

and

(photon #1 travel from path  $L_1$ )

⊗ (photon #2 travel from path  $S_2$ )

will be cut off by the time window of the coincidence circuit if the travel time difference between the long and short paths is larger than the time window or will contribute to the noise if the time window of the coincidence circuit is not short enough.

The coincidence counting rate was predicted to be

$$R_c = \frac{1}{4} R_o \cos^2 \left\{ [(\omega_1 + \omega_2) \cdot \Delta T + \phi_1 + \phi_2] / 2 \right\} \\ = \frac{1}{4} R_o \cos^2 \left\{ \delta_1 / 2 + \delta_2 / 2 \right\} \quad (4)$$

where  $\Delta T$  is the travel time difference

between the long and short paths of the two independent interferometers and  $\phi_1$ , any other phase shift. Eq. (4) shows a 100% interference modulation for an arbitrary time difference of  $\Delta T$ , in other words, the interference pattern will be the same even when the optical path difference of the interferometer is much longer (infinite) than the coherence length of the field. It was suggested that this prediction leads to a violation of Bell's inequality and a quantum non-local effect. Compared to the historical E.P.R. experiments, which used polarization as a measured quantity, this experiment is looking at the direct phase correlation between the long-long and short-short path amplitude. Unlike the other second order interference experiments which superpose the two photons at a beamsplitter, the photon pair never "come" together in this proposed experiment. The "interference" can not be explained by the idea of definite field phase relation at the beamsplitter as usually do. The experiment simply counts the timing of the detections and through the timing analyzer to distinguish the coincidence detection and the noncoincidence detection, i.e., the phase relation will be explored through the timing of detection and the width of the time window of the timing analyzer.

Since then, two experiments have reported the observation of the quantum mechanical effect.<sup>(8),(9)</sup> However, it seems that these two experiments did not provide enough data and information to support the conclusion that the quantum non-local effect was detected. Both experiments reported only one visibility measurement for one setting of the optical path difference of the interferometers. More measurements are required to test Franson's calculation. We report a similar two-photon interference experiment with more measurements and different results.

The experimental arrangement is shown in Fig. 3. A 351 nm CW Argon laser line was used to pump a 50 mm long

potassium dihydrogen phosphate (KDP) nonlinear crystal for optical parametric down conversion. Nonlinear optical parametric down conversion produces correlated pairs of photons which satisfy the phase-matching condition:

$$\omega = \omega_1 + \omega_2, \quad \mathbf{k} = \mathbf{k}_1 + \mathbf{k}_2, \quad (5)$$

where  $\omega$  and  $\mathbf{k}$  are the frequency and the wave vector of the pumping beam,  $\omega_1$ ,  $\omega_2$  and  $\mathbf{k}_1$ ,  $\mathbf{k}_2$  are the frequencies and the wave vectors of the generated light quanta. The KDP crystal was cut at TYPE I phase-matching angle for degenerate frequency but divergent propagation direction of signal and idler light quanta. The 702 nm photon pair was selected by pinholes and traveled to two independent Michelson interferometers (I and II). Two detectors  $D_1$  and  $D_2$  with 10 Å spectral filters (centered at 702 nm) were placed after the interferometers. The detectors were avalanche photodiodes operated in Geiger mode with less than 1 nanosecond rise time and less than 50 picosecond time jitter. The output pulses from  $D_1$  and  $D_2$  were sent to a coincidence counting circuit which had a 100 picosecond time window to record  $R_c$ , the counting rate of coincidence and  $R_1$ , the counting rate of single detector.

Before the experiment, we first measured the coherence length of the down converted field by using our Michelson interferometer. It was concluded by direct observation with out any spectral filter that the first order interference pattern disappeared at about 50  $\mu$  from the white light condition. The coherence length of the pump laser beam was measured to be much much longer than 50 mm (limited by the interferometer).

The experiment was done by two steps:

First, interferometer II was set with  $\Delta L_1 = 5$  mm from white light condition and interferometer II was scanned from the white light condition to 5 mm. 96% second order and 82% first order interference visibilities were observed at the beginning of the scanning (near white light condition), see Fig. 4 and Fig. 5. The first order interference visibility dropped to 0 at 400  $\mu$  (with 10 Å spectral filter). The second order interference visibility is reported in Fig. 6. It is important to mention that the noise counting rate was not subtracted from the visibility calculation (the same as the other reports)

$$\mathcal{V} = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}}. \quad (6)$$

Because the short time window of the coincidence measurement, the noise counting rate for the second order interference measurement was almost zero. On the other hand, the noise counting rate from single detector (first order interference measurement) was significant. It is clear from Eq. (6) that the contribution of the noise counting rate will result a lower visibility. It can not be concluded that the "second order coherence length is longer than the first order coherence length", or "the visibility of second order interference is better than that of the first order interference" as in some of the early reports.

The second order visibility was measured to be zero at  $\Delta L_2 = \Delta L_1 = 5$  mm, this is different than Franson's prediction.

Second step of the experiment, interferometer II was moved 400  $\mu$  at a time from  $\Delta L_2 = 400$   $\mu$  to  $\Delta L_2 = 6$  mm and interferometer I was scanned around the position of equal path difference,

$\Delta L_2 \approx \Delta L_1$ , for 50  $\mu$  and the visibility of the second order interference was measured. Fig. (7) reports this measurement. It is clear that the second order interference visibility (for  $\Delta L_2 \approx \Delta L_1$ ) did drop to zero at about 4 mm from the white light condition which is much shorter than the coherence length of the pumping laser beam. However, it is also true that the visibility for equal optical path difference measurement did not drop to zero as quick as that for non-equal optical path difference measurement which was reported at step one. It takes six to seven times longer distance to approach 10% visibility when the optical path difference are equal (compare Fig. (6) and Fig. (7)).

The alignment of the optical system is important. The alignment of the interferometers were checked before taking of date. We use He-Ne laser and sodium discharge light to check the alignment for  $\Delta L$  from white light condition to 10 mm.

A classical model predicts that the visibility of second order interference in the case of long coincidence time compared to the coherence time of the down converted beam approaches

$$V = \frac{1}{2} \exp -(\Delta L / L) \quad (7)$$

where  $\Delta L = \Delta L_1 = \Delta L_2$ , and  $L$  is a constant in length which expresses the precision to which the phase matching condition in Eq. (5) is satisfied. The same result may be obtained from a quantum mechanical model. The details of these models will be presented later elsewhere.

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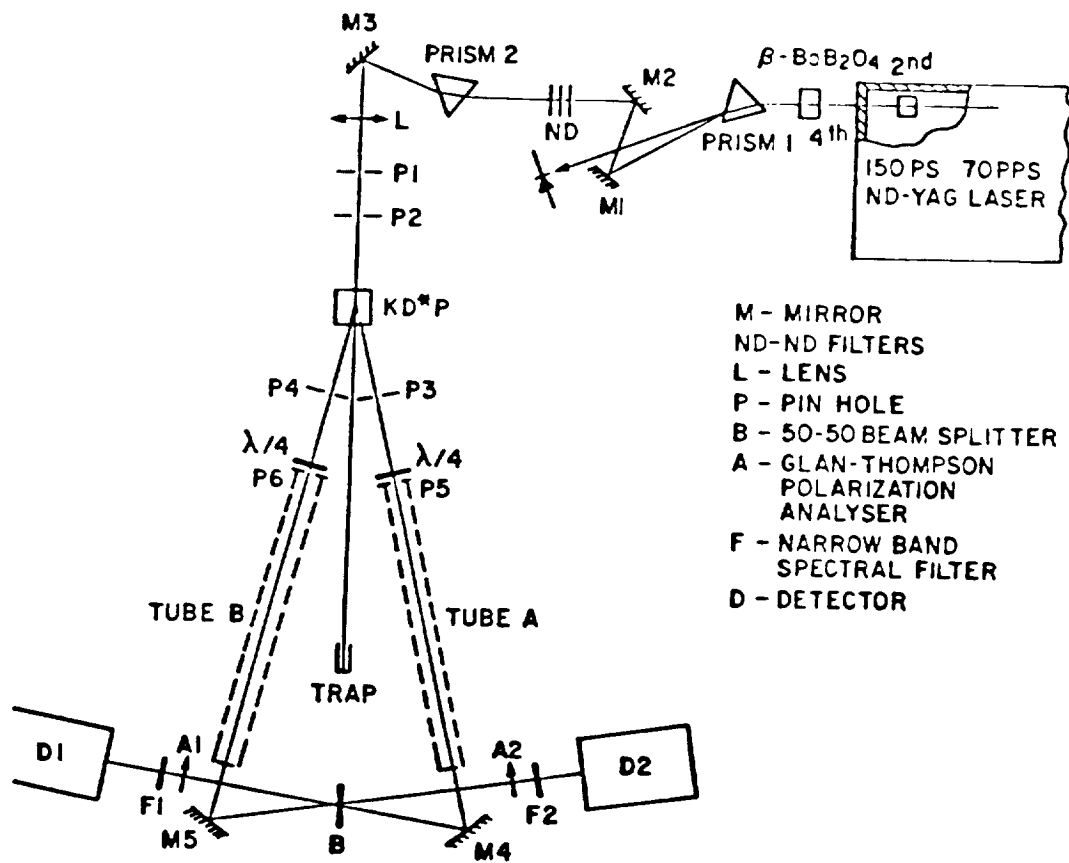


Figure 1. First EPR experiment using parametric down conversion.

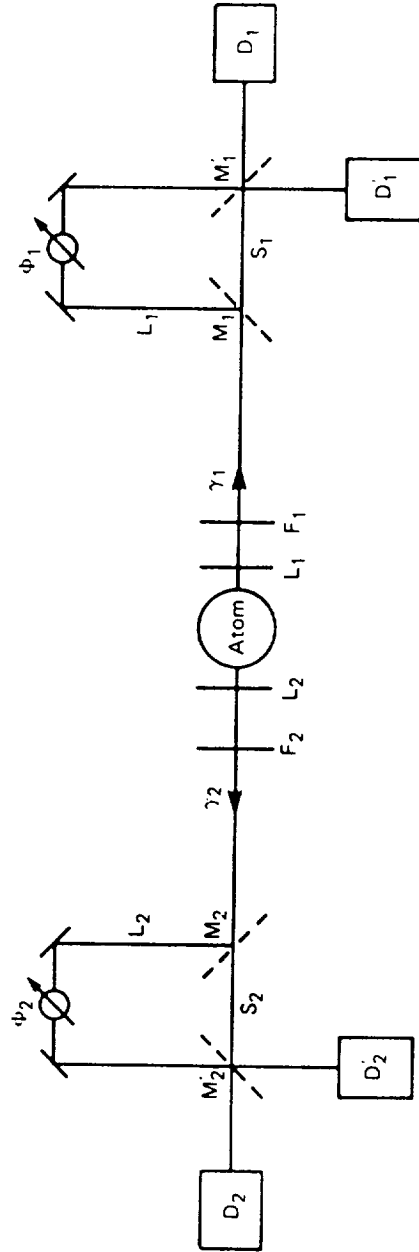


Figure 2. Proposed Franson's experiment.



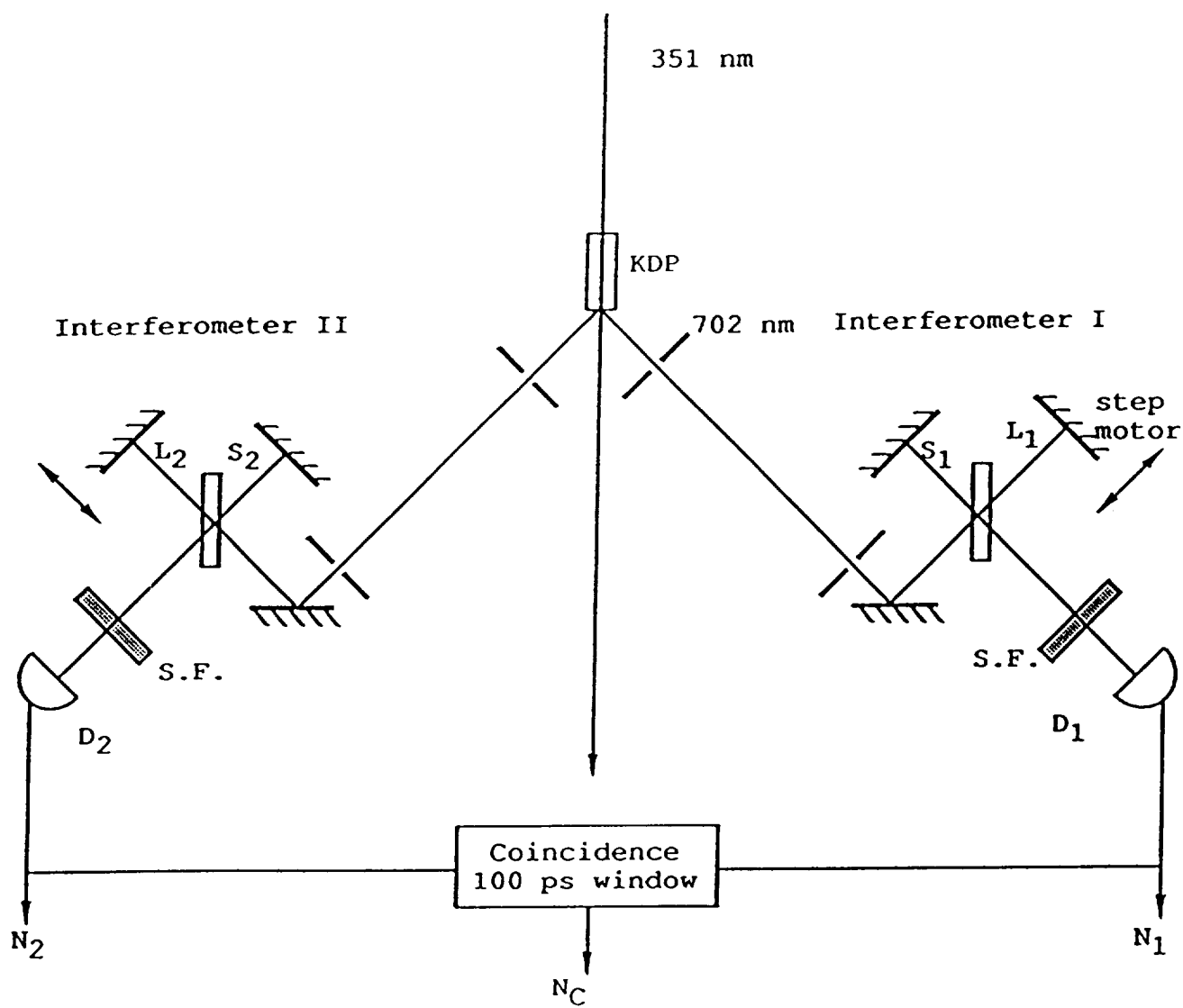


Figure 3. Schematic diagram of the experiment.

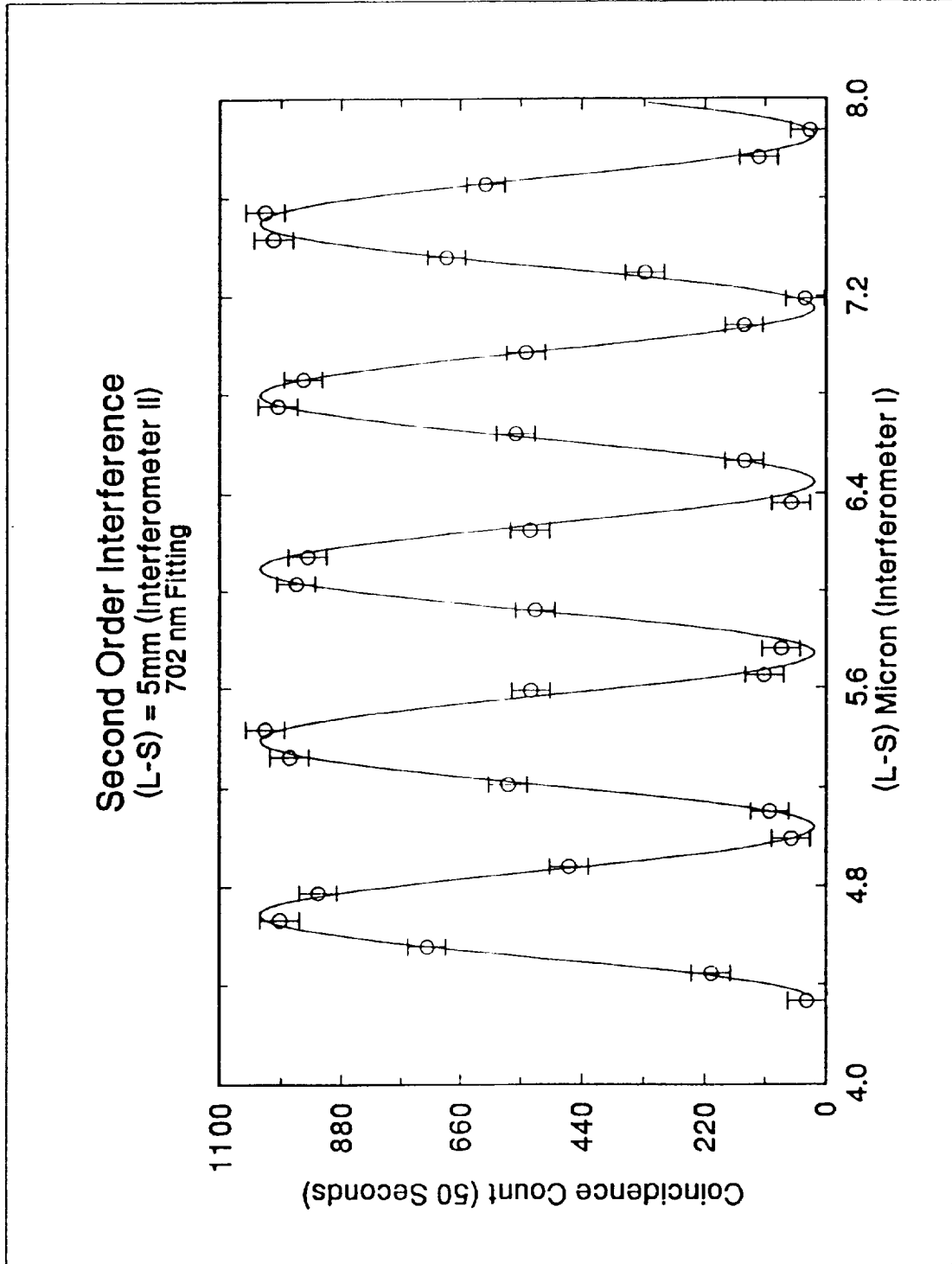


Figure 4. Second order interference (near white light condition).

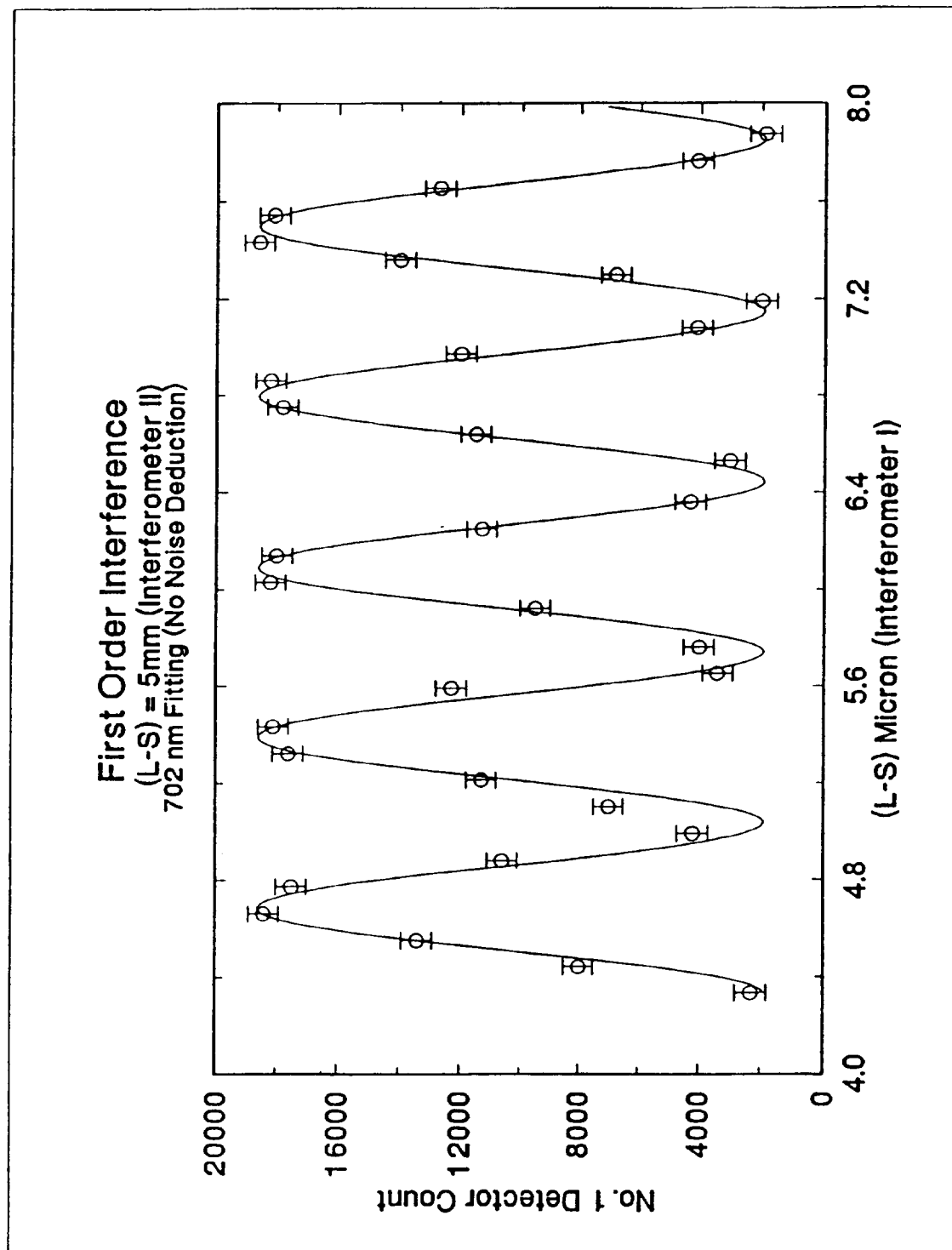


Figure 5. First order interference (near white light condition).

Second Order Interference Visibility  
(L-S) = 5 mm (Interferometer II)

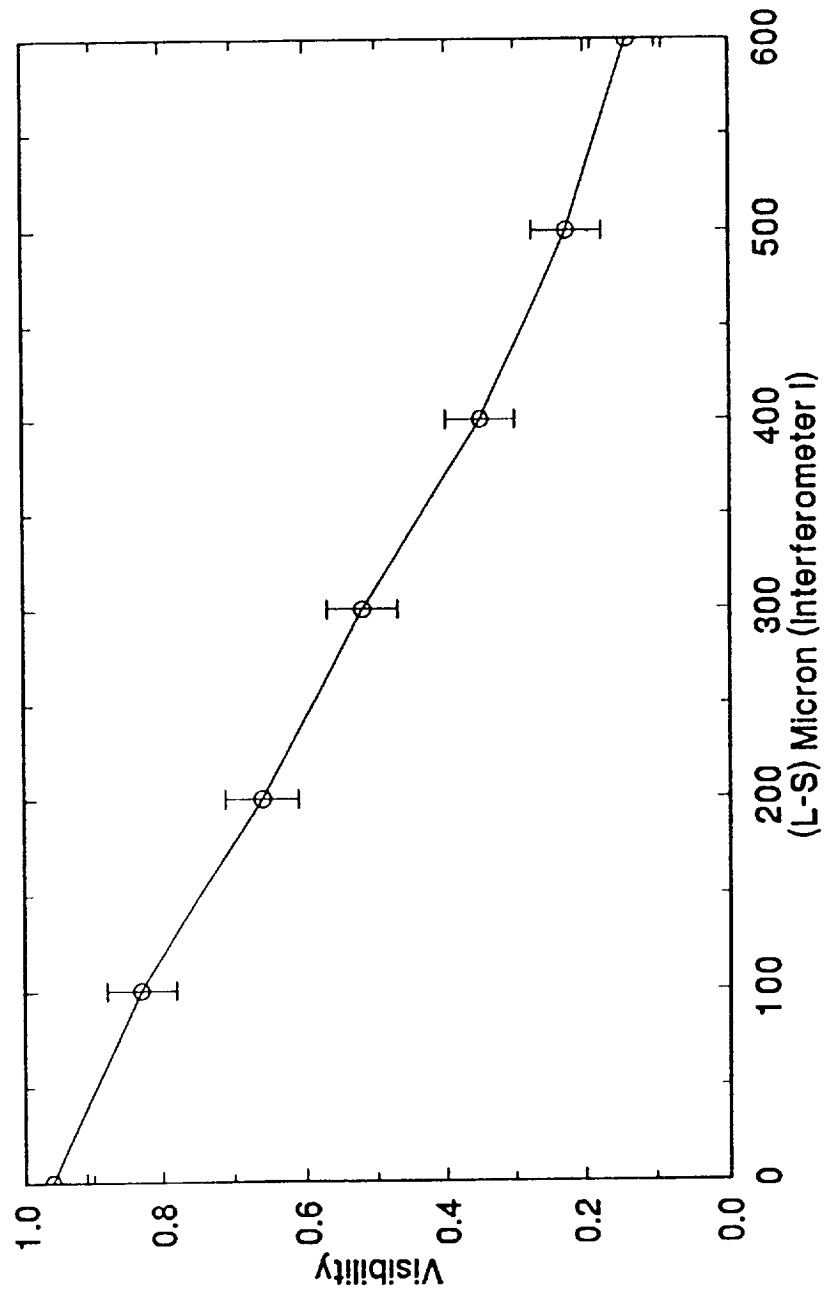


Figure 6. Second order interference visibility (non-equal optical path differences).

## Second Order Interference Visibility Outside Coherence Length

$0.5 \exp(-(L-S)/2500)$  Fitting

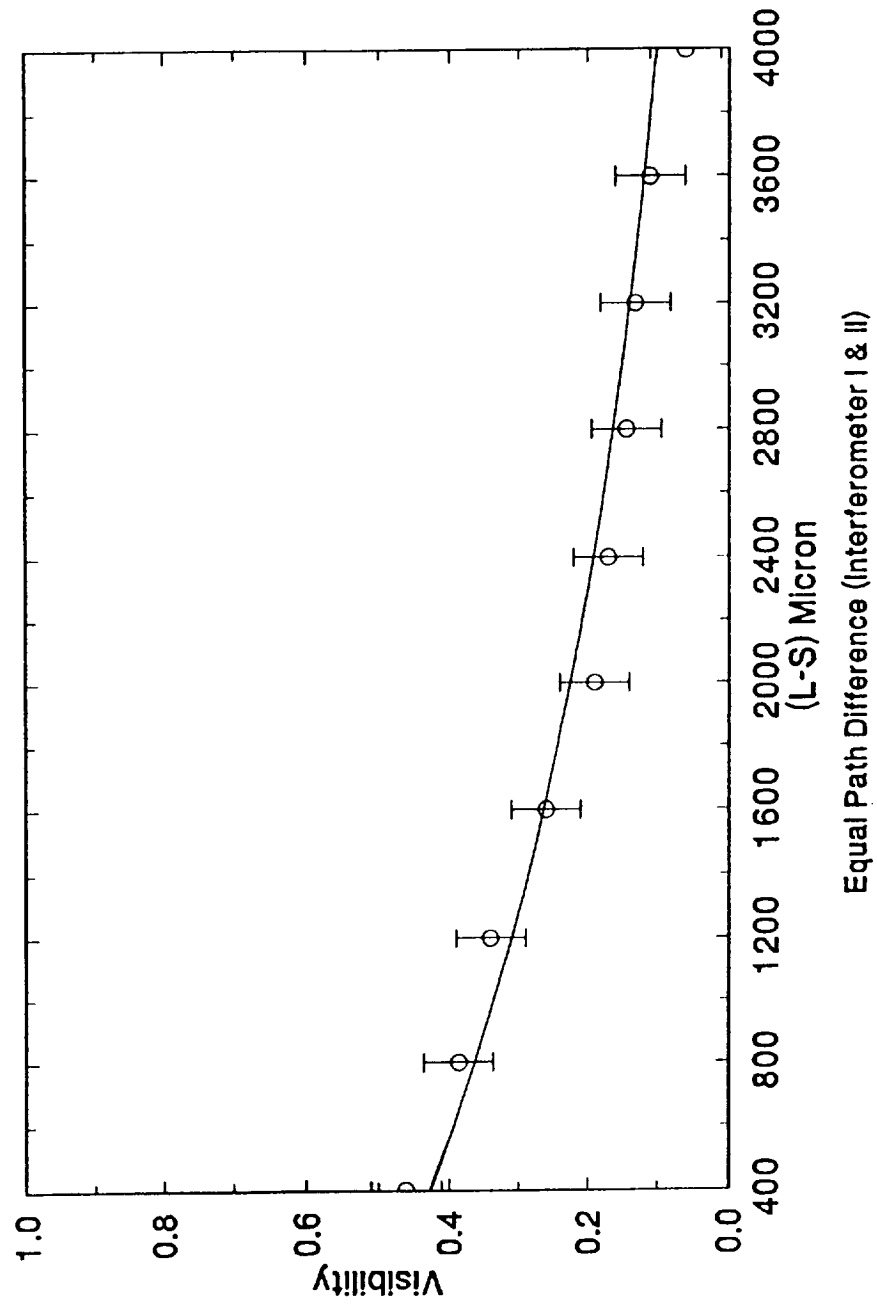


Figure 7. Second order interference visibility (equal optical path differences).